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UNITED STATES PATENT APPLICATION FOR

**A SWITCHED-CAPACITOR CONTROLLER TO CONTROL THE RISE  
TIMES OF ON-CHIP GENERATED HIGH VOLTAGES**

Inventor:

Michael S. C. Chung

Prepared by:

WAGNER, MURABITO & HAO  
Two North Market Street  
Third Floor  
San Jose, CA 95113  
(408) 938-9060

## A SWITCHED-CAPACITOR CONTROLLER TO CONTROL THE RISE TIMES OF ON-CHIP GENERATED HIGH VOLTAGES

### Technical Field

5       The present invention relates to a switched-capacitor circuit for controlling the rise times of on-chip generated high voltages.

### Background Art

10       Non-volatile memory chips are used in a wide variety of electrical applications, computers, communications devices, consumer electronics, and any other application where data must be retained when power is no longer being supplied. Flash erasable programmable read-only memory (EPROM) chips are non-volatile memory chips which also offer the ability  
15       of being programmed and erased. In order to program and erase these flash EPROM chips, high voltages varying from 10 to 16 volts are typically required to perform the programming and erasing operations. These high voltages are commonly referred to as  $V_{pp}$ . The high voltages are usually generated on the flash EPROM chips based on an externally supplied low  
20       voltage power supply ( $V_{cc}$ ). Circuitry, such as "charge pumps," on the flash EPROM chip take the  $V_{cc}$  power supply voltage and outputs the requisite higher  $V_{pp}$  voltage. The charge pumps are basically voltage multiplication circuits, and the techniques for their construction are well known to those skilled in the non-volatile memory arts.

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It is oftentimes desirable to control the rise times (e.g., ramp rate) of the on-chip generated high voltages (i.e.,  $V_{pp}$ ) for flash EPROMs. This is

due to the fact that if the rise time of  $V_{pp}$  were too fast, it may impose undue stress on the flash EPROM memory core cells when the  $V_{pp}$  is applied to the control gate of the cell during channel hot electron programming or programming via Fowler-Nordheim tunneling.

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Therefore, there exists a need for a circuit or method which is capable of accurately control the rise time of an on-chip generated high voltage or  $V_{pp}$ . The present invention offers a unique, novel solution which is especially relevant to Flash EPROM and other non-volatile memories which require high voltages for their program and/or erase procedures.

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DISCLOSURE OF THE INVENTION

The present invention pertains to a switched-capacitor circuit for accurately controlling the rise times of on-chip generated high voltages.

- 5 An on-chip charge pump is used to generate a high voltage (VPP) from an external power supply voltage (VCC). This high voltage signal (VPP) can be used to program Flash memory cells. The capacitor of a switched capacitor circuit is selectively switched between ground and a given node voltage. This produces a stair-stepped ramp function. The period of the
- 10 steps is controlled according to a clock signal or oscillator. The frequency of this clock signal may be altered to generate the desired period. The voltage increases of the steps is regulated by a reference voltage multiplied by a ratio between two capacitor values. Thereby, the switched capacitor system accurately controls the rise-time of the VPP signal as a function of
- 15 the frequency of the clock signal and the ratio of the two capacitor values.

### BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and form a part of this specification, illustrate embodiments of the invention and, together with the description, serve to explain the principles of the invention:

Figure 1 shows a circuit diagram of the currently preferred embodiment of the present invention.

Figure 2 shows an actual shape of the VPP during the PGM phase.

Figure 3 shows a plot of the VPP waveform through one PGMV-PGM cycle.

Figure 4 shows exemplary outputs from a VPP generator with rise-time control using a switched capacitor system according to the currently preferred embodiment of the present invention.

BEST MODE FOR CARRYING OUT THE INVENTION

The present invention pertains to a switched-capacitor circuit for controlling the rise times of on-chip generated high voltages. In the following detailed description of the present invention, numerous specific details are set forth in order to provide a thorough understanding of the present invention. However, it will be obvious to one skilled in the art that the present invention may be practiced without these specific details or by using alternate elements or methods. In other instances well known methods, procedures, components, and circuits have not been described in detail as not to unnecessarily obscure aspects of the present invention.

Referring to Figure 1, a circuit diagram of the currently preferred embodiment of the present invention is shown. The circuit comprises a charge pump 101. Alternatively, a voltage multiplication circuit may be implemented in place of the charge pump 101. The charge pump 101 is typically comprised of a series of MOS diode connected transistors and coupling capacitors driven by two-phase non-overlapping clocks generated from a primary clock signal labeled OSC. The OSC signal is usually the output of an on-chip ring oscillator circuit. The OSC signal is also input to the divide by N counter 102. The divide by N counter 102 is a binary digital counter that performs a "divide by N" function where N is a power of two. The output from the divide by N counter 102 is a clock signal, OSCD, whose frequency is equal to that of OSC divided by N where  $N=2^M$ , with M being the width of bits of the binary counter represented by the counter. The OSCD output from the divide by N counter 102 is fed as an input to the non-overlapping two phase clock generator 103. The clock

generator 103 generates two non-overlapping clock phases, PHI1 and PHI2, which have the same frequency as the output from counter 102. The two non-overlapping clock phase signals are input to block 104. Block 104 creates two "gated" versions of the PHI1 and PHI2 signals, referred to as PHI1A and PHI2A. The PHI1A and PHI2A signals are controlled by the control signals PGM and PGMV. When both PGM and PGMV are low, both PHI1A and PHI2A are pulled up to logic high (e.g.,  $V_{CC}$ ). When PGMV is high and PGM is low, PHI1A is pulled up to  $V_{CC}$  while PHI2A is grounded. Finally, when PGMV is low and PGM is high, PHI1A is logically equivalent to PHI1 while PHI2A is equivalent to PHI2. In other words, when PGM is high and PGMV is low, PHI1A and PHI2A function as a pair of non-overlapping two phase clock signals. It should be noted that, by design, there will never be a situation whereby both PGM and PGMV are both high. Circuit block 105 comprises a voltage level shifter that converts the control signal ENVPP to a level shifted inverted signal, VPPONBH.

Circuit block 106 comprises a "keeper" device 107 which is controlled by the high-voltage inverter made up of devices 108, 109, and 110. When the control signal ENVPP is low, the gate of "keeper" device 107 is grounded and node VPP is kept at  $V_{CC}$ . When ENVPP goes high, the gate of device 109 is connected to VPP and device 109 behaves as a reverse biased diode-connected transistor, and the connection from  $V_{CC}$  to VPP is broken. This allows VPP to be pumped up by the charge pump 101 when ENVPP goes high.

Circuit block 111 is a constant ramp generator. It contains a P-channel pass transistor 112, a capacitor divider network, and a switched capacitor network. More specifically, the capacitor divider network is comprised of capacitor 113 and capacitor 114. The switched capacitor network is comprised of capacitor 115 connected to a pair of NMOS pass devices 116 and 117. The NMOS pass devices 116 and 117 are driven by the pair of non-overlapping clock phase signals PHI1A and PHI2A. Also included in circuit block 111 is a high gain CMOS comparator 118 and an NMOS pull down stack made up of devices 119, 120, and 121. An inverter 122 is driven by the input signal VPOK which is output from circuit block 123. Also included is an initialization device 124.

Circuit block 123 is used to detect the final voltage. It is comprised of a P-channel pass device 125, a capacitor divider network, a high gain CMOS comparator 126, an NMOS pull down stack, a pseudo PMOS inverter, a CMOS inverter 127, and initialization devices. The NMOS pull down stack is comprised of devices 128 and 129. The pseudo PMOS inverter is comprised of devices 130 and 131. And the initialization devices include transistors 132, 133, and 134.

The operation of the entire system is now described in detail. The beginning of a high voltage programming operation is signified by the control input signal ENVPP going high from a previous low state. At the same time, the PGMV signal is activated (e.g., brought to VCC) to first initiate a Program Verify operation. This is done to verify whether the selected bits are already in a programmed state. If they are, then the subsequent program or PGM operation will be skipped. During the



Program Verify phase, PHIA is high while PHI2A is grounded. Hence, the node 135 in circuit block 111 is grounded and at the same time, capacitor 115 is isolated from node 136 of circuit block 111. The feedback loop consisting of comparator 118 and pull-down devices 119, 120, and 121 forces VPP to be regulated to a value given by the equation:

$$VPP_1 = VREF \left( \frac{C_1 + C_{2A}}{C_1} \right)$$

where  $C_1$  = capacitance of capacitor 113 and  $C_{2A}$  = capacitance of capacitor 114. Simultaneously, the regulation circuitry inside circuit block 123 is also active. The comparator and capacitor divider network of capacitors 137 and 138 and the rest of the circuitry (including devices 128 and 129) attempt to regulate VPP to a value given by:

$$VPP_2 = VREF \cdot \left( \frac{C_3 + C_4}{C_3} \right) \dots$$

where  $C_3$  = capacitance of capacitor 137 and  $C_4$  = capacitance of capacitor 138. However, the values of capacitors 113, 114, 137, and 138 are chosen such that:

$$\left( \frac{C_3 + C_4}{C_3} \right) > \left( \frac{C_1 + C_{2A}}{C_1} \right)$$

Therefore, during Program Verify, VPP is regulated to the smaller value given by VPP1 of the first equation given above. It should be noted that VPP2 sets the upper limit of VPP during the program phase when VPP is ramped up from the VPP1 value in a controlled fashion. During the Program Verify (PGMV) phase then, VPPCOMP2 of circuit block 123 stays

low and the VPOK signal also stays low since VPPDIV2 is always less than VREF during PGMV.

At the conclusion of the PGMV phase, assuming that the selected bits are not all programmed already, a program (PGM) phase is launched during which PGMV is grounded and the PGM signal is asserted high. During PGM, the PHI1A and PHI2A function as a pair of non-overlapping clock phases. The capacitor 115 of circuit block 111 is then periodically switched between VSS (ground) and node 136. It should be noted that capacitor 115 can be approximated by an equivalent resistor connected between node 136 and VSS with a value given by:

$$R_{EQ} = \frac{T_{SW}}{C_2}$$

where Tsw is the period of either PHI1A or PHI2A, and where C<sub>2</sub> = capacitance of capacitor 115.

Now, invoking the "virtual ground" concept at the inputs of comparator 118 of circuit block 111, it can be determined that the regulation feedback loop in circuit block 111 forces the average current flowing from VPPDIV1 to VSS (ground) through the switched capacitor 115 as represented by its equivalent resistor to a value as given by:

$$I_{AV} = \frac{VREF}{R_{EQ}} = \frac{VREF \cdot C_2}{T_{SW}}$$

Since  $I_{AV}$  is also flowing through the capacitor 113, whose bottom plate is held at a fixed average value of  $VREF$ , the voltage on its top plate (VPP) must be changing at a rate given by:

$$5 \quad \left\langle \frac{dVPP}{dt} \right\rangle = \frac{I_{AV}}{C_1}$$

Substituting the two equations, one comes up with the following equation:

$$10 \quad \left\langle \frac{dVPP}{dt} \right\rangle = \left( \frac{C_2}{C_1} \right) \left( \frac{VREF}{T_{sw}} \right)$$

In both of the two above equations, the notation  $\langle \rangle$  denotes the time average of the quantity contained inside the angular brackets. From the earlier discussion:

$$15 \quad T_{sw} = \frac{T_{osc}}{N}$$

where  $T_{osc}$  is the period of the on-chip ring oscillator driving the charge pump 101.

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The actual shape of the VPP during the PGM phase is a staircase as shown schematically in Figure 2. It can be seen that:

$$\Delta VPP = VREF \cdot \left( \frac{C_2}{C_1} \right); \dots$$

$$\Delta t = T_{sw} = \frac{T_{osc}}{N}; \dots$$

From the equations above, one can calculate  $\left\langle \frac{dVPP}{dt} \right\rangle$  is a function of a ratio of the two capacitances C2 and C1 and also of T<sub>osc</sub>. Since (C2/C1) is expected to be highly insensitive to process, temperature and power supply variations, the only sensitivity to these variables lies in T<sub>osc</sub>, which is the period of the on-chip ring oscillator.

During the PGM phase, VPP will keep increasing with an average  $dVPP/dt$  until VPP reaches a value given by VPP2, at which time VPPCOMP2 will reach an average value high enough to drive VPOK to VCC. When this happens, device 121 will be turned off and the feedback loop in circuit block 111 will be broken and the circuit block 111 will no longer be able to control VPP. The regulation loop in circuit block 123 then takes over and regulates or clamps VPP to a constant final value given by VPP2 given in the previous equation. After a pre-determined time interval has expired, the PGM signal is brought low, signifying the end of the program phase. The ENVPP signal is then brought low, discharging VPP back down to VCC. After a sufficient amount of discharge time has elapsed, PGMV and ENVPP are again activated to initiate another Program Verify operation to check whether the previous PGM operation was successful or not. If unsuccessful, another PGM phase can be launched, and the whole PGMV-PGM-PGMV cycle is repeated. During each PGM phase, VPP will be pumped up from its value of VPP1 (attained using the PGMV phase) with  $\langle dVPP/dt \rangle$  until it reaches VPP2.

Figure 3 shows a plot of the VPP waveform through one PGMV-PGM cycle. It can be seen that the signal starts at VCC, increases during

PGMV, and then increases incrementally in a stair-step fashion with the value of each step given by  $V_{REF} * (C2/C1)$ . The period of each step is given by  $T_{SW}$ . The voltage is then clamped at VPP2 for the remainder of the PGM cycle.

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Figure 4 shows exemplary outputs from a simulation of the VPP generator with rise-time control using a switched capacitor system according to the currently preferred embodiment of the present invention. Right after time  $t=0$ , the ENVPP control signal goes from 0 volts to 5 volts. It stays at 5 volts for 5 microseconds. At which point, the ENVPP control signal drops back down to 0 volts for half a microsecond. It then goes back up to 5 volts for another 5 microseconds. This process can repeat. At the same time, right after time  $t=0$ , the PGMV phase initiates at a constant 6 volts. Upon initiation of the PGM phase, the VPP voltage ramps up in a stair-case pattern up to 10 volts. At the conclusion of the PGM phase, the voltage falls back down to 5 volts until the next PGMV phase begins anew. Again, this process can repeat.

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Therefore, a switched-capacitor circuit for controlling the rise times of on-chip generated high voltages is described. While the present invention has been described in particular embodiments, it should be appreciated that the present invention should not be construed as limited by such embodiments, but rather construed according to the below claims.

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